

COSMIC RAY MODULATION AND MERGED INTERACTION REGIONS

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ABSTRACT

Beyond several AU, interactions among shocks and streams give rise to "merged interaction regions" in which the magnetic field is turbulent. The integral intensity of > 75 MeV/Nuc cosmic rays at Voyager is generally observed to decrease when a "merged interaction region" moves past the spacecraft and to increase during the passage of a rarefaction region. When the separation between interaction regions is relatively large, the cosmic ray intensity tends to increase on a scale of a few months. This was the case at Voyager 1 from July 1, 1983 to May 1, 1984, when the spacecraft moved from 16.7 to 19.6 AU. Changes in cosmic ray intensity were related to the magnetic field strength in a simple way. It is estimated that the diffusion coefficient in merged interaction regions at this distance is $\sim 0.6 \times 10^{22}$ cm²/s.

1. Introduction. Variations in the intensity of galactic cosmic rays > 75 MeV/nucleon near 11 AU on scales ranging from approximately a day to a year were found to be related to the interplanetary magnetic field in observations from Voyagers 1 and 2 from June, 1982 to August, 1983 (Burlaga et al., 1985a). The long-term variation of cosmic ray intensity was related to the strength and separation of interaction regions. It decreased or remained relatively low when interaction regions were strong and closely spaced, and it increased when the interaction regions were weaker and widely spaced. These results are consistent with the idea that modulation is caused by diffusion in turbulent magnetic fields (Morrison, 1956) and the observation that modulation effects propagate outward from the sun at the solar wind speed (McDonald et al., 1981). A non-steady model of the 11-year variation which incorporates diffusion and propagation of shells of disturbances has been constructed by Perko and Fisk (1983).

The purpose of this paper is to extend the analysis of Burlaga et al. (1985a) to examine the relation between cosmic ray intensity and the interplanetary magnetic field from July 1, 1983 to May 1, 1984, using Voyager 1 data. During this interval the spacecraft moved from a heliocentric distance of 16.7 AU to 19.6 AU and from a heliographic latitude of 20° to 23° .

2. Observations. The intensity of cosmic rays > 75 MeV/nucleon, measured by the CalTech/University of New Hampshire/Goddard Space Flight Center experiment is shown in Figure 1, together with the strength of the interplanetary magnetic field measured by the GSFC magnetometer (N. Ness, Principal Investigator). The magnetic field strength was normalized by the spiral magnetic field strength, $B_p = 4.75 \times (1 + r^2)^{1/2} / r^2$. Thus, the magnetic field fluctuations in Figure 1 are perturbations on the large-scale average magnetic field, which are produced by dynamical interplanetary processes.

Figure 1 shows a correlation between B/B_p and the cosmic ray intensity C : C generally decreases during the passage of an interaction region or merged interaction region ($B/B_p > 1$) and it increases during the passage of a rarefaction region ($B/B_p < 1$). A similar correlation was observed near 11 AU by Burlaga et al. The net effect in the period shown in Figure 1 is an overall increase in cosmic ray intensity. The cosmic ray intensity profile is the result of a competition between the effects of interaction regions and those of rarefaction regions. In this interval, the interaction regions were relatively weak ($(B/B_p)_{\max} < 2.5$) and the corresponding decreases in C were relatively small, while the rarefaction regions were large in extent, allowing more than enough time to recover from the individual decreases.

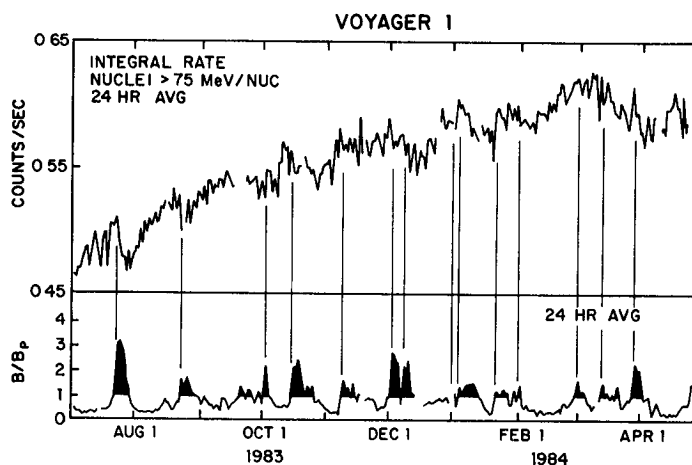


Fig. 1 Intensity of cosmic rays > 75 MeV/nuclei versus time (top) and magnetic field strength relative to the spiral field strength versus time (bottom).

3. Model. Burlaga et al. (1985a) modeled the variation of cosmic ray intensity observed near 11 AU from July, 1982 to August, 1983 with the following set of equations:

$$\frac{dC}{dt} = -D (B/B_p - 1) \quad \text{when } B/B_p > 1 \quad (1)$$

$$\frac{dC}{dt} = R \quad \text{when } B/B_p \leq 1 \quad (2)$$

where D and R are constants and B/B_p is the measured magnetic field strength as a function of time. Using the 24-hour averages of $B/B_p(t)$ shown in Figure 1, choosing $D = 0.004$ (counts/sec/day) and $R = 0.002$ (counts/sec/day) and taking the initial value of C at July 1, 1983, these

equations were integrated to obtain the model cosmic ray intensity profile shown in Figure 2. The observed 24-hour averages of $C(t)$ for > 75 MeV/nucleon cosmic rays are also plotted in Figure 2, for comparison. Note that the model curve has been plotted with a constant offset of 0.03 (counts/sec/day) for the sake of clarity, but its initial value can be chosen to be identical to the observed value for the integration of (1) and

(2). Between March 10 and March 20 there was a decrease in cosmic ray intensity which is not predicted, because there was no large increase in B/B_0 at this time (see Figure 1). Except for this anomaly, the model provides a very good approximation to the cosmic ray observations throughout the 10-month interval.

A theoretical basis for the model given by (1) and (2) has recently been given by Chih and Lee (1985). They found that under certain assumptions

$$\frac{dC}{dt} = -\frac{V}{L} (C - C_0) - \frac{V}{K} C_0 \frac{\delta B}{B_0}, \quad (3)$$

where K is the diffusion coefficient, V is the solar wind speed, L is a characteristic length and δB is a measure of the fluctuations of B . It has been observed that $\delta B/B_0 \approx 0.3$ between 1 AU and 5 AU, varying slowly with distance as $r^{-1/3}$ (Burlaga et al., 1982), so it is reasonable to take $\delta B/B_0 = 0.3 B/B_0$ in (3). In this case the second term on the RHS of (3) has the same form as (1), and one can use our value of D to estimate the diffusion coefficient K . With $D = 0.004$ (counts/sec/day), $V = 400$ km/s, $C_0 = 0.55$ counts/sec and $\delta B/B_0 = 0.3$ one finds $K = 0.6 \times 10^{22} \text{ cm}^2 \text{ s}^{-1}$. This is somewhat smaller than the value chosen by Chih and Lee (because we used $\delta B/B_0 = 0.3$), but it is close to the value for the diffusion coefficient used by Perko and Fisk (1983) to describe the 11-year variation. Identifying the first term on the RHS of (3) with R in (2), and taking $C - C_0 \approx 0.03$ counts/sec, one finds that $R = 0.002$ (counts/sec/day) implies $L \approx 4$ AU.

In Figure 3 we show spectra of the components of B (upper curve), the magnitude of B (lower curve) and the magnetic helicity times frequency (fH_m) computed from one hour average Voyager 1 data from July 1, 1983 to May 1, 1984, using the fast Fourier transform method with 26 degrees of freedom, without detrending or filtering the data (Matthaeus and

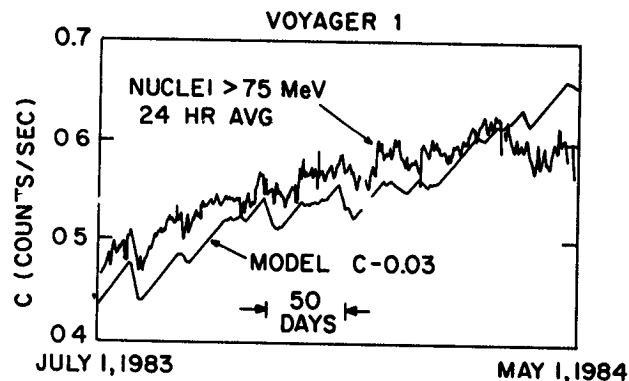


Fig. 2 The result of a model (see text) together with a plot of the observed counting rates.

Goldstein, 1982). Positive values of magnetic helicity are denoted as circles, negative values as triangles. Assuming that plasma is convected past the spacecraft at the mean solar wind speed in the interval, \bar{V} , the frequency f_c corresponding to the correlation length L , is $f_c = \bar{V}/L$, and this is shown by the arrow in Figure 3.

The spectrum of power in the components of B has the form $f^{-5/3}$, expected for homogeneous turbulence in the range 4×10^{-6} Hz to 2×10^{-5} Hz, corresponding to periods from 14 hours to 3 days. This is consistent with earlier results showing that the fluctuations in interaction regions are turbulent. At periods between 4 days and 15 days, the spectrum of power in the components of B was $\propto f^{-1}$, which is probably either a remnant of the spec-

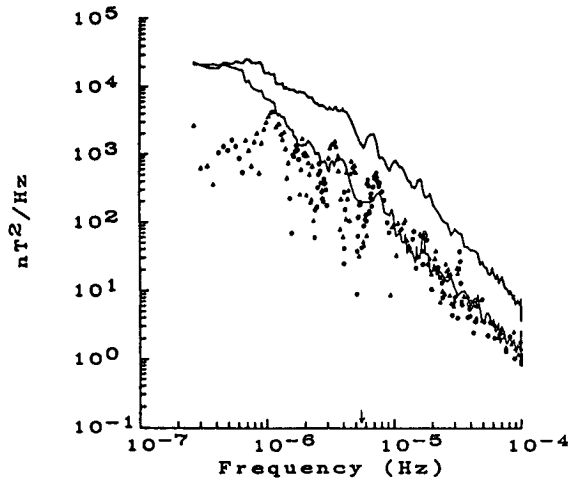


Fig. 3 Power spectra of the magnetic field (see text).

trum of fluctuations introduced at the source (Goldstein et al., 1984; Burlaga et al., 1985b) or evidence of an inverse cascade of magnetic helicity expected in fully developed MHD turbulence (Frisch et al., 1975; Montgomery and Matthaeus, 1981). If the former interpretation is correct, its presence is another indication that turbulence did not develop sufficiently to modify the initial spectrum in this quasi-stationary flow system, despite the long time available for evolution, viz. ~ 18 AU/400 km/s \rightarrow 78 days.

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